SUMMARY OF HIGH LEVEL TURBULENCE OVER UNITED STATES

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ABSTRACT

A comprehensive study was made of pilot-reported occurrences of high level turbulence (more commonly referred to as CAT) over the United States from September 1960 through August 1962. The data consist of 12,126 reports of moderate or severe turbulence above 15,000 ft. The tabulations presented include the distribution of turbulence by months, seasons, altitude, and geographical location, and its association with such meteorological items as: the position with respect to the jet stream, curvature of the jet stream, strength of the isotach center, streamline curvature, troughs, closed or cut-off Lows, and mountain waves. Some additional data are included for levels as high as 70,000 ft.

1. INTRODUCTION

The U.S. Weather Bureau has undertaken a comprehensive study of high level turbulence using a much larger and far more complete set of pilot reports than has been available for previous studies. The actual tabulation and analyses have been limited to reports of moderate or greater turbulence above 15,000 ft. m.s.l. Pilot reports of turbulence in or near towering cumulus clouds or thunderstorms have been eliminated from the tabulations and analyses.

It is fully recognized that this analysis is limited to the areas of reported turbulence. It is not known whether there was no turbulence in the other areas or simply that there were no planes flying over these areas at the time or altitude that turbulence occurred. The pilot reports are highly subjective and qualitative, as the intensity of the turbulence felt is dependent among other things on the type and weight loading of the plane and the air speed and angle of attack. Even so, these reports constitute a valuable set of data and every attempt should be made to extract as many useful conclusions from them as possible.

Pilot reports were collected from weekly summaries tabulated by all Weather Bureau Airway Forecast Centers, from teletypewriter data on Air Force circuits, and from additional data on a monthly basis from the National Weather Records Center at Asheville. Daily tabulations were made of all reports of moderate or greater turbulence occurrences above 15,000 ft., exclusive of those in or near towering cumulus clouds or thunderstorms. Since October 1, 1961, data pertaining to the occurrences have been placed on punch cards and standard print-outs are available to any interested research or operational group.

2. RESULTS

GENERAL DISTRIBUTIONS

Over the 24-month period from September 1960 through August 1962, there were 12,126 reports of moderate or greater turbulence occurrences available for the study. The mean monthly distribution (fig. 1) shows a maximum in February and a minimum in August. It is interesting to note that there were 5,623 reports in the last 12 months as compared to 6,503 in the first 12 months, in spite of the fact that the number of high level flights and the efficiency of the collection of the pilot reports is likely to have increased gradually throughout the entire period. The decrease could have been caused by fewer or smaller turbulence areas in the atmosphere, but it could have resulted from improved forecasting so that the pilots could better avoid these high threat areas or could fly through these areas at reduced flying speeds which would reduce the frequency of reports of the more serious turbulence.

The overall distribution of the occurrence of moderate or greater turbulence with altitude is shown in figure 2. The frequency of turbulence reports by altitude is highly dependent on the frequency of flights by altitude. Unfortunately, accurate information on the latter is difficult to obtain. However, discussions with aircraft operational groups suggest a maximum of flight frequency around 30,000 to 31,000 ft. and then a rapid decrease. Thus, it appears that the peak at 35,000 to 36,000 ft. is not due to any bias in actual flight frequencies but is associated with the average height of the maximum wind and the tropopause.

The average monthly height of the reported turbulence occurrences showed a regular variation throughout the year ranging from a minimum of 30,200 ft. in March to a maximum of 34,000 ft. in July. The monthly median height ranged from a minimum of 30,900 ft. in March to a maximum of 34,300 ft. in July. It is difficult to attribute the above monthly trend to any bias in the flight frequencies and it appears more likely to be associated with changes in meteorological conditions, such as a higher tropopause and level of maximum winds, during the summer months.

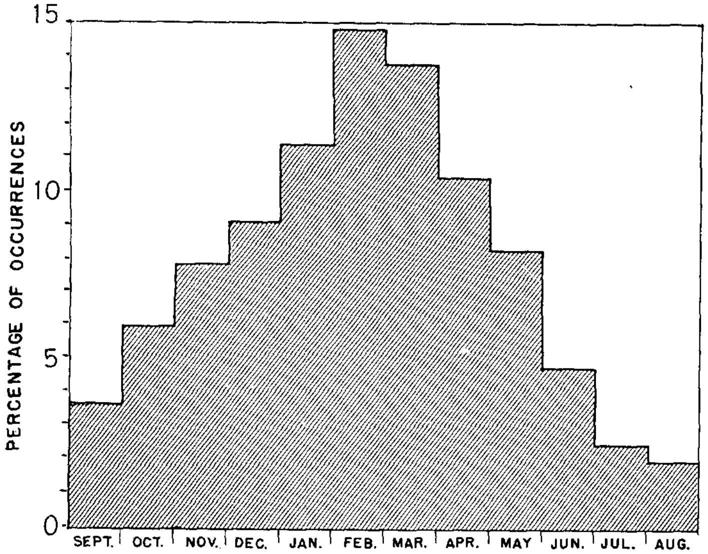

FIGURE 1.—Mean monthly distribution of moderate or severe turbulence September 1, 1960, through August 31, 1962.

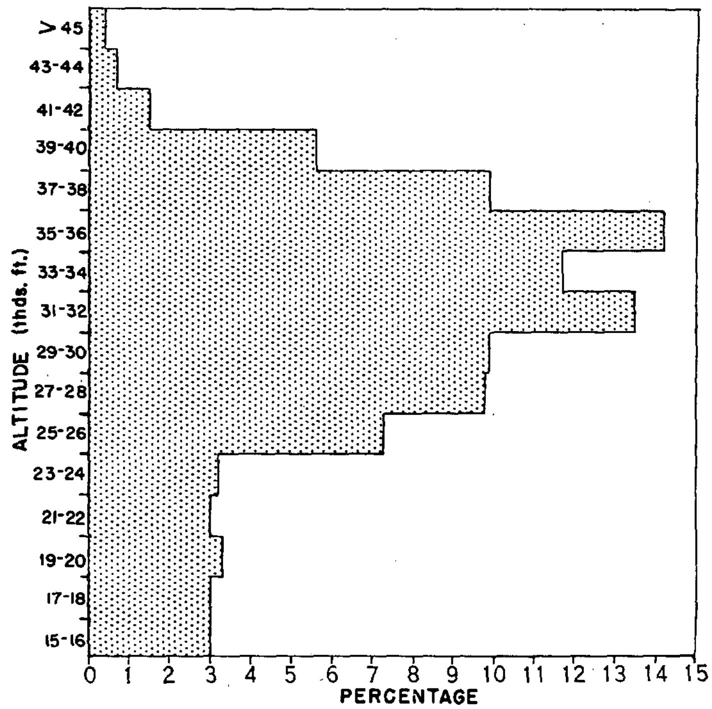

FIGURE 2.—Distribution of moderate or severe turbulence by altitude.

The distribution of over 12,000 reported occurrences of moderate or greater turbulence during the 2-year period is shown in figure 3 using 5° latitude-longitude "squares." Obviously this distribution is greatly biased by the flight routes. However, it appears that the concentration along and to the lee of the Rocky Mountains is due more likely to the influence of the mountains in producing mountain waves and their associated turbulence than to any flight bias in this region. The peak over Kentucky, West Virginia, and western Virginia may also have some validity since it is slightly south of the more frequent flight routes into New York.

The average number of reported occurrences of moderate or greater turbulence for each month and season is shown in figure 4 for seven arbitrarily chosen regions: Far West, Rocky Mountains, Southwest, Midwest, South-Central, Northeast, and Southeast. There was a winter maximum in each region except in the Northeast and Southeast where the maxima are in the spring. There was a summer minimum in each region except in the Northeast where the minimum was in the fall. The results in general confirm and greatly extend some of the earlier findings by Clem [1].

These variations may be associated with actual wind patterns rather than with some flight bias. In all regions except the Rocky Mountains and the Far West the number of occurrences in the fall was considerably less than half the number in the winter months. In the Rockies and the Far West, the fall months appear to be relatively more important than in the other regions which may be due to the increase in the mountain wave activity over the Rocky Mountains in the fall. As mentioned before, spring appears to be relatively more important in the Northeast and Southeast than in the other regions.

It is evident from all of the above distributions of turbulence occurrences that there can be some moderate or severe turbulence expected along all flight routes, at all altitudes, and at any time of the year.

SPECIFIC METEOROLOGICAL PATTERNS

This section of the paper deals with the association of the reported occurrences with various meteorological patterns from September 1, 1961, through August 31, 1962. The reports of moderate or greater turbulence were tabulated as to whether they occurred (1) within 150 mi. to the left of the jet, (2) within 150 mi. to the right of the jet, or (3) more than 150 mi. from any jet in which case they were listed as non-jet cases. The jet positions were those analyzed by the National Meteorological Center (NMC) and transmitted on the Maximum Wind Analysis facsimile charts. Left and right sides were defined looking downwind along the jet. For the occurrences associated with the jet, tabulations were made with respect to whether the curvature of the associated segment of the jet was cyclonic, anticyclonic, or straight. Occurrences between two jets (with the jets not over 300 mi. apart) were tabulated and further subdivided as to whether the jets were parallel, converging, or diverging.

The occurrences of moderate or greater turbulence were tabulated with respect to whether the curvature of associated height contour lines (300-mb. facsimile chart) was cyclonic, anticyclonic, or straight. Occurrences which were associated with strong wind flow normal to the Rocky or Appalachian Mountains were tabulated as mountain-wave cases. Occurrences within 150 mi. of a trough line (as shown on the NMC 300-mb. facsimile

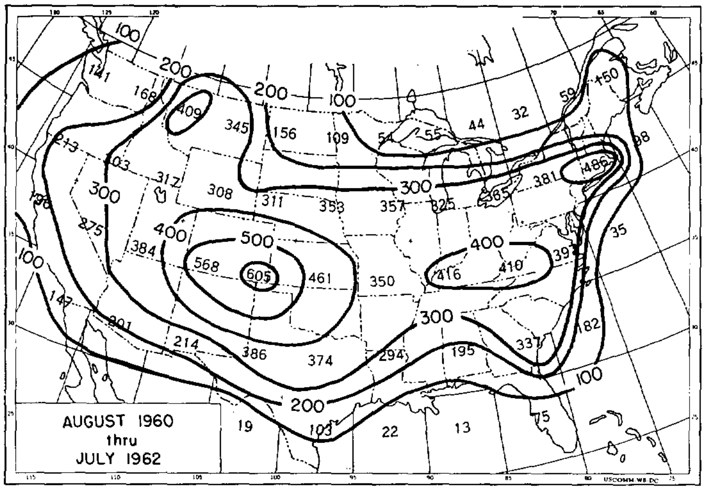

FIGURE 3.—Distribution of moderate or severe turbulence over the United States.

chart) were listed with a further breakdown as to whether the occurrences were ahead of or behind the trough line. Tabulations were made of the occurrences associated with closed or cut-off Lows.

Jet Stream Association.—Of the 5,623 reports of moderate or greater turbulence during the year, 36 percent were within 150 mi. to the left or the cold side of the jet, 28 percent were within 150 mi. to the right of the jet, and 36 percent were more than 150 mi. from any jet (non-jet cases). In any study or forecast of turbulence limited to 150 mi. to the left or cold side of the jet, 64 percent of all the occurrences would have been neglected.

TABLE 1.—*Seasonal distribution of the association between reported turbulence occurrences and the jet stream*

Season	Within 150 mi. to left	Within 150 mi. to right	Non-jet
Fall (Sept., Oct., Nov.)	34%	31%	35%
Winter (Dec., Jan., Feb.)	39	29	32
Spring (Mar., Apr., May)	36	26	38
Summer (June, July, Aug.)	29	30	41

The seasonal distribution, as shown in table 1, indicates that the association between the reported occurrences and the left or cold side of the jet was most important in the winter and spring when the jet streams were stronger and better organized, and less effective in the summer. During the summer months, 71 percent of all the reported occurrences were either on the right side or more than 150 mi. away from any jet axis.

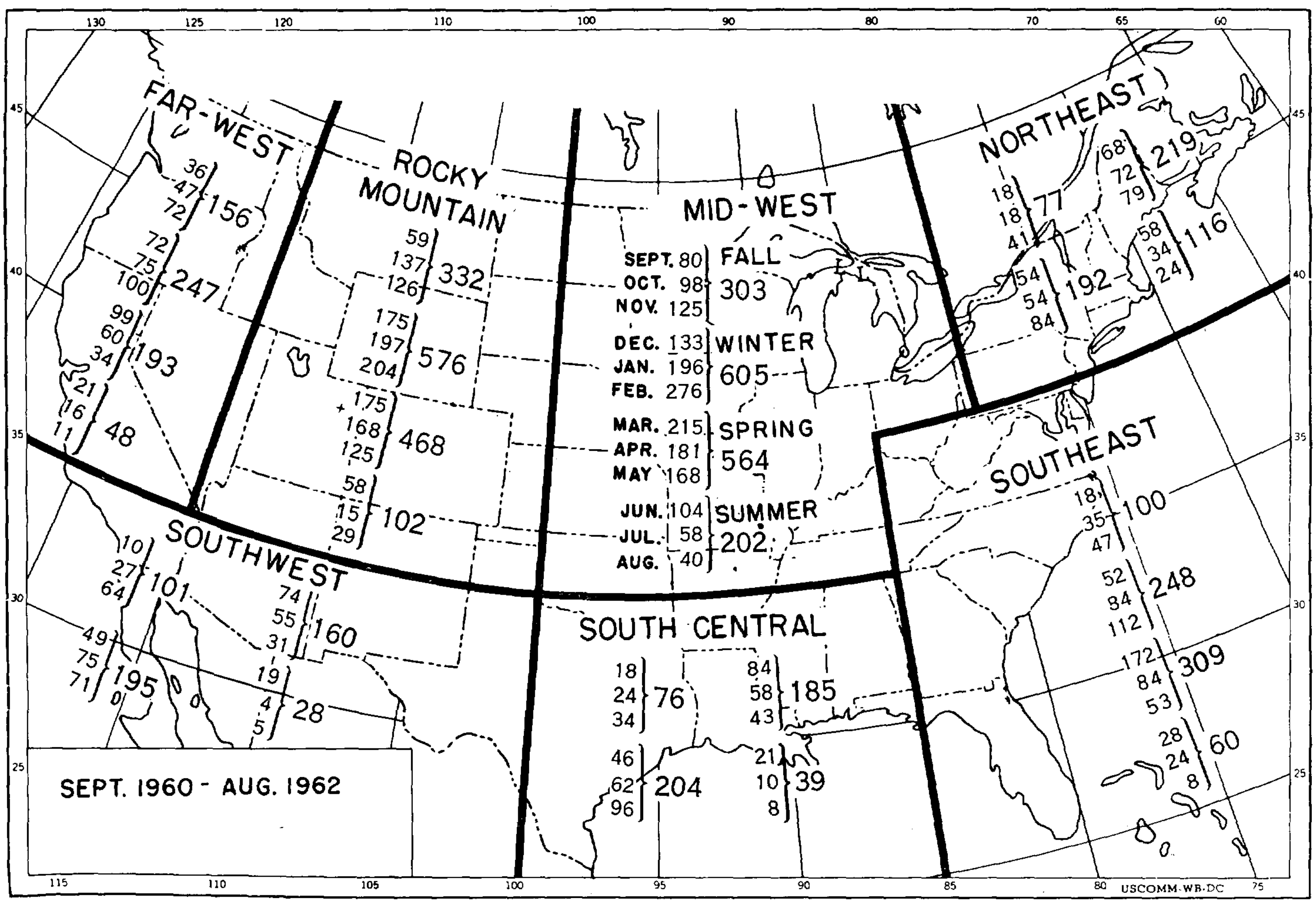

FIGURE 4.—Distribution of moderate or severe turbulence by months and seasons.

TABLE 2.—*Seasonal distribution of curvature of the jet associated with the reported turbulence occurrences*

Season	Cyclonic (percent)	Anti-cyclonic (percent)	Straight (percent)
Fall	47	20	33
Winter	26	28	46
Spring	28	38	34
Summer	46	17	37

Of the occurrences reported within 150 mi. on the left side of the jet, the curvature of the associated segment of the jet stream was cyclonic 29 percent, anticyclonic 30 percent, and straight 41 percent of the time. Of the occurrences reported within 150 mi. to the right side of the jet, the curvature of the associated segment of the jet stream was cyclonic 37 percent, anticyclonic 26 percent, and straight 37 percent of the time. This tabulation indicates that when turbulence was reported, the segment of the associated jet stream was cyclonically curved only slightly more often than it was curved anticyclonically. Certainly, in a large majority of the cases, the segment of the jet associated with the reported turbulence was either anticyclonically curved or straight and these situations cannot be neglected in a study or forecast of high level turbulence.

The distribution of the curvature of the jet stream associated with all the reported occurrences within 150 mi. on either the left or right side of the jet, as shown by table 2, indicates that cyclonically curved jets were more frequently associated with the occurrences in the summer and fall months, anticyclonically curved jets in the spring, and long straight jets in the winter months.

Of the total number of reported occurrences of moderate or greater turbulence, 43 percent were located within the 100-kt. isotach and 8 percent were within the 150-kt. isotach. A seasonal breakdown with respect to the occurrences within the 100-kt. isotach indicated that 56 percent of all the occurrence reports in the winter months were within the 100-kt. isotach and only 12 percent of all the summer reports were within the 100-kt. isotach center.

Of all the moderate or greater turbulence reports, 11 percent were between two jets (jets 300 mi. or less apart). A further breakdown indicated 5 percent occurred between parallel, 3 percent between converging, and 3 percent between diverging jets.

Circulation Patterns.—Of all the reported moderate or greater turbulence occurrences during the year from September 1, 1961, through August 31, 1962, 35 percent were associated with cyclonically curved, 29 percent with anticyclonically curved, and 36 percent with straight height contours. Again, there was only a slightly greater frequency of reported occurrences with cyclonically rather than anticyclonically curved height contours. If only the turbulence occurrences associated with cyclonically curved contours were considered, 65 percent of the turbulence situations would have been neglected.

The seasonal distribution of the curvature of the height contours associated with the reported turbulence occurrences (table 3) shows the cyclonic patterns are relatively much more frequent in the fall and summer months and the long straight contours are relatively more frequently associated with the reported turbulence during the winter months. In the spring months, the reported occurrences seem equally likely to be associated with cyclonic, anticyclonic, or straight contours.

In this study, it was found that 21 percent of all the reported occurrences were tabulated as possible mountain-wave type. Of all the reported occurrences, 16 percent were found to be located within 150 mi. ahead of or to the rear of a trough line (as indicated on the NMC 300-mb. facsimile chart). In the trough study, there were as many occurrences ahead of as there were to the rear of the trough line. This study indicated that only 3 percent of all the reported occurrences were associated with a closed or cut-off Low.

The results in table 4 indicate that the association of reported turbulence with troughs is greater in the fall than in the winter and spring when the association with the left or cold side of the jet is more pronounced. The percent of occurrences associated with closed Lows is quite low throughout the year but is relatively greater in the fall and spring. The table shows considerable mountain-wave type occurrences all during the year but that they were relatively more important in the winter than in the other seasons.

HIGHER LEVEL TURBULENCE

At the present time, there is an increasing interest in the problem of turbulence at levels well above 40,000 ft., especially in connection with the proposed supersonic jet transport operations. Some turbulence data above 40,000 ft. from a high-altitude sampling program (March 1958 through August 1959) were available at the time of this study. These results are shown in table 5.

It is interesting that the percent of flights with no turbulence was considerably higher in the 60,000–70,000-ft. layer than in either of the other layers. In the highest

TABLE 3.—*Seasonal distribution of contour curvature associated with the reported turbulence occurrences*

Season	Cyclonic (percent)	Anti-cyclonic (percent)	Straight (percent)
Fall	52	22	26
Winter	27	28	45
Spring	33	34	33
Summer	47	24	29

TABLE 4.—*Seasonal distribution of the association of turbulence occurrences with troughs, closed Lows, and mountain waves*

Season	Trough (percent)	Closed Low (percent)	Mountain wave (percent)
Fall	26	5	22
Winter	11	1	30
Spring	14	4	23
Summer	18	1	18

TABLE 5.—*Higher level turbulence data*

Altitude (thsd. ft.)	Number of flights	Flights with—		
		No turbulence (percent)	Light or greater (percent)	Moderate or greater (percent)
40–50	35	40	60	34
50–60	139	49	51	34
60–70	228	66	34	25

Distribution with respect to intensity

Altitude (thsd. ft.)	Occurrences	Light (percent)	Moderate (percent)	Severe (percent)
40–50	27	44	48	8
50–60	135	41	43	16
60–70	142	55	38	7

layer, 45 percent of all the reported occurrences were moderate or greater as compared to 59 and 56 percent in the other two layers. However, 25 percent of all the flights in the 60,000–70,000-ft. layer encountered moderate or greater turbulence. This indicates that turbulence may be of considerable importance in the stratospheric levels.

Most of the reported turbulence occurrences were above the tropopause and well into the stratosphere. The mechanism for the production of turbulence in the stratosphere may be considerably different from that involved in the troposphere. The actual wind speeds and wind shears in the lower stratospheric levels are not nearly as strong as in the troposphere near the jet stream levels. However, there are temperature and density discontinuities about which wave motions and turbulence may be generated in ways similar to those suggested by Reiter [9]. Many more turbulence occurrence data will be needed before this stratospheric turbulence can be understood.

3. SUMMARY AND CONCLUSION

This study provides confirmation for ideas which have been presented by other workers in this field. The data on the association of turbulence with the jet stream and its associated vertical and horizontal wind shear support earlier work by Harrison [8] and George [6]. The data on the association of turbulence with air flow over the mountains support earlier works by Clodman et al. [2], Harrison [8], and Colson [3]. The data on the association of turbulence with troughs confirm earlier findings by Colson and Rustenbeck [4] and Colson [5]. This work shows some relation between turbulence and upper-level closed Lows which has been mentioned by Harrison [7], Colson and Rustenbeck [4]; however, the percent of such occurrences was found to be quite low in this study.

While this study confirms the above-mentioned associations, it is apparent from this and earlier studies, Colson [3], [5], that no one meteorological pattern or model will be sufficient for the understanding and forecasting of high level turbulence over the entire country and throughout the year. There appears to be more than one mechanism effective in the production of small-scale eddies which affect aircraft in flight. These include (1) strong jet stream configurations with their associated horizontal and vertical wind shears, (2) sharp major and even minor troughs moving across the country with their associated directional shears, and (3) airflow over mountain barriers with the proper wind shear and stability. Other mechanisms may be involved in the turbulence occurrences associated with cirrus cloud formations and with high pressure or anticyclonic circulation patterns.

In general, it will be necessary to make a complete and detailed analysis of the atmospheric conditions and to forecast the changes in these conditions in order to make an accurate forecast of high level turbulence on a local scale which will be useful for aviation operations. High level turbulence is not a simple phenomenon and it will not be possible to arrive at any simple criterion or magic number which will solve the problem of forecasting high level turbulence accurately.

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